LEILAC2 Demonstration Plant's Preliminary Front End Engineering Design (Pre-FEED) Report

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- HeidelbergCement AG
- Lhoist Recherche et Developpement SA
- Calix Limited
- Port of Rotterdam
- CIMPOR
- IKN
- Engie Laborelec
- Geological Survey of Belgium
- BGR
- Politecnico Milano
- Centre for Research & Technology-Hellas
- CEMEX

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1 Executive Summary

The project LEILAC2 - Low Emissions Intensity Lime And Cement – aims to demonstrate a breakthrough technology that can capture a cement or lime plant's unavoidable process emissions for minimal energy, therefore providing a viable and cost effective decarbonisation solution. Process CO_2 emissions from the cement and lime industries have been identified as an important challenge for climate change mitigation given that these emissions are inherent to the production process and therefore difficult to avoid.[1]

Building on the success of the previous H2020 LEILAC1[2] project – which captures around 5% of a typical cement plant's CO_2 emissions using Calix's new capture technology - LEILAC2 will develop, build and validate a module capturing 20% of a typical cement plant's CO_2 emissions. LEILAC2 will benefit from significant private sector funding. This module will be low cost, scalable, replicable and retrofittable; be efficiently integrated into an operational plant; demonstrate the use of multiple fuel sources (particularly electricity with rapid ramping, to enable renewables load-balancing); and show how it can be used to immediately, cheaply and either incrementally or fully retrofitted to all cement plants - enabling both Europe's cement and lime industries to dramatically reduce their unavoidable emissions while maintaining their international competitiveness.

LEILAC2 will also provide a near-term, realistic business case for a transport and storage network in Europe's main industrial region, using its low-cost capture plant as a catalyst for wider CCUS operations. However, this work does not form part of Milestone 1, as there are no current plans to store the Demonstration Plants CO_2.

The LEILAC2 partners are committed to knowledge sharing as widely as possible, and this Pre-FEED summary represents the evolution, achievements, and intentions of this initial phase of the project. The Pre-FEED phase has been run as a network of collaborative, cross partner working groups, focussed on assessing technical scale up options and de-risking the Demonstration plant development. This report summarises the main research, development and engineering actions contributing to the first formal project stage-gate. It covers the period from the commencement of the project in April 2020 to the Go/No-go decision in March 2021.

Throughout the pre-FEED phase a number of research, modelling, design evaluation and enhancement studies have been successfully undertaken for the Demonstration plant, with the aim of reducing the major scale-up risks. A detailed Basis of Design (BoD) of the Demonstration plant was created, fulfilling all of the objectives of the project. The host plant site has been reviewed and the optimal location of the LEILAC2 demonstration plant at Hannover has been investigated. This phase has also included the identification of integration points, development of a staged commissioning plan and a constructability analysis. Safety and environmental risk assessments have been completed. In addition to a recommendation on the design option for development, costs for the Demonstration plant's construction have been evaluated to be within a ±30% level of accuracy.

[1] 1.5 IPCC report. Chapter 4, 3.4.5 CO_2 capture, utilization and storage in industry
[2] www.project-leilac.eu

The resulting BoD was assessed in March 2021 in detail by an external Value Assurance Review panel of industry experts, over the course of two weeks. It was also reviewed and approved by the project's Executive Board. It was then finally reviewed and approved by the project's General Assembly.

The project will now enter the next stage of development – Front End Engineering Design (FEED) phase. During the FEED phase, the de-risking focussed approach will continue with the aim of reducing all technical risks to 'low', and of further developing and optimising the engineering BoD, along with its integration into the HeidelbergCement cement plant at Hannover, Germany. The site development and procurement plans will be produced, and a ±15% cost estimate generated for approval. This will underpin the Final Investment Decision to be taken in the coming months.

This report initially provides a high-level overview of the pre-FEED phase results, covering the background, risks, project rationale, design basis, engineering, conclusions, and next steps. The rest of the document provides more detail per topic, outlining the options analysis work undertaken between April 2020 to March 2021.

1.1 The Project - LEILAC 2 (Low Emissions Intensity Lime And Cement)

The LEILAC2 Demonstration Plant is a 4 x scale up of the LEILAC 1 pilot, taking 20% of the host plants raw feed, and will be developed on HeidelbergCement's operational cement plant in Hannover, Germany.

The LEILAC2 consortium is led by technology provider Calix, and further comprises Heidelberg Cement, CEMEX, Lhoist, Cimpor, IKN, CERTH, Royal Belgian Institute of Natural Sciences, BGR, Polimi, Engie Laborelec and Port of Rotterdam.

The project is also supported by GCCA, CEMBUREAU, ECRA, EuLA, VDZ and the University of Clausthal as the External Advisory Board. This five-year project is funded by the European Commission through the Horizon 2020 research and innovation programme (€16M, grant no. 884170), and some of the consortium members (€18M) including cash contributions towards the development of the demonstration plant and in-kind contribution for staff.

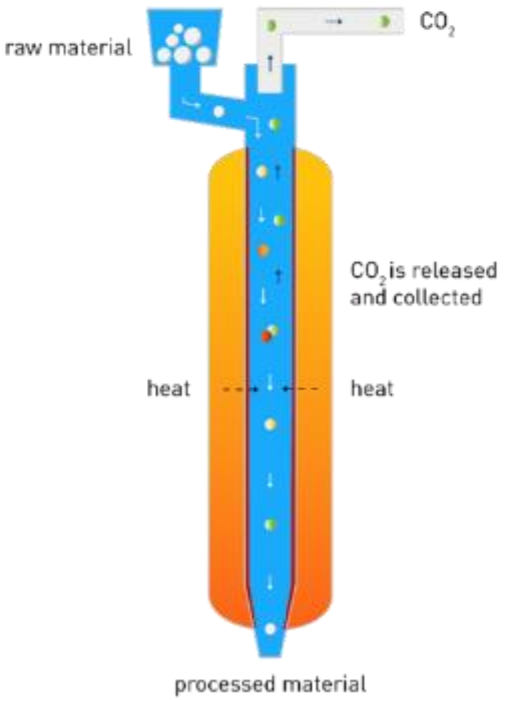

Figure 1 – LEILAC Technology design

Using Calix's LEILAC technology the released process CO_2 is not contaminated or diluted.
This carbon capture process does not require additional energy or chemicals.

The LEILAC2 project is based on a technology developed by Calix, which aims to enable the efficient capture of the unavoidable process emissions from lime and cement production. The process CO_2 which is chemically released from the limestone accounts for more 60% of the total CO_2 emitted from lime and cement processing, depending on the type of fuel used. The LEILAC technology seeks to simply re-engineer the existing process flows of a traditional calciner, by indirectly heating the material being processed via a special steel vessel. This unique system enables pure CO_2 to be captured, in the case of limestone ($CaCO_3$), as it is released during calcination to lime (CaO), as the furnace exhaust gases are kept separate. This elegant solution requires no additional chemicals or processes.

LEILAC2 will develop, build, operate and test a 960 tonne per day (raw meal) demonstration plant at HeidelbergCement's plant in Hannover, Germany, demonstrating at a commercial scale that over 95% of the process CO_2 emissions can be captured, while integrating with the host plant.

Once built the Demonstration plant will be trialled and validated under actual operating conditions, with a staged fuels commissioning programme and a variety of test campaigns over a 6 month period, to confirm the technology's performance and integration is as expected, paving the way for full scale demonstration. Once proven at a suitable scale this may become the Best Available Technology for both the cement and lime industries. For a plant using this technology, the main additional 'cost' would only be for compressing the CO_2 for further useful purposes (CCU) or safely storing it underground (CCS).

The LEILAC2 project commenced on the 1st April 2020, and will run for five years completing March 2025. The project is built around a number of phases and milestones including Pre-FEED, FEED, and a combined Engineering, Procurement and Construction phase (EPCM), and subsequent commissioning and testing/operations.

1.1.1 LEILAC2 Milestones & Timeline

The project is structured around distinct engineering and development phases and milestones with two key stage gates at Milestone 1 and 2 consisting of formal Go/ No-go decisions by the General Assembly. This structure ensures the project proceeds with the endorsement and support of the entire consortium, and that it does so on a risked basis, regarding the estimated budget and chance of success.

Milestone number	Milestone name	Related work package(s)	Due date (in month)	Date	Means of verification
MS1	Feasibility (pre-FEED) study – go/no-go decision	WP3	12	Mar-21	D3.1 Pre-FEED report and GA decision
MS2	FEED study, Final Investment Decision (go/no-go decision)	WP3	20	Nov'21	D3.3 FEED report and GA decision
MS3	Construction complete / Operations commence	WP3	40	Jul'23	D3.5 Demonstration Plant Acceptance Document
MS4	Demonstration plant verified	WP2	45	Dec'23	D2.7 Demonstrator Test programme result summary
MS5	Integrated operations verified, and commercialisation report developed	WP2	60	Mar'25	D2.10 Report on the potential for Rapid Commercialisation of the LEILAC Technology, and anticipated rollout
MS6	CO_2 storage and use business case delivered	WP4	60	Mar'25	D4.5 CO_2 storage or use Business case

Table 1 - LEILAC2 Milestones

1.1.2 Project Objectives

The project objectives, as outlined within the H2020 Grant agreement, are to **construct a Demonstration Plant to:**

- Capture **20% of a full-scale cement plant's** (and roughly 100% of a large lime shaft kiln's) process emissions – capturing around 100 ktpa of pure CO_2 for minimal energy penalty.
- Prove the **effective retrofit and full integration** of the Demonstration Plant into the host cement plant's operations.
- Prove the **efficiency and stability** of the complete cement-kiln process and resulting clinker quality when operating largely on LEILAC calcining technology.
- Prove that the Demonstration Plant forms an **easily replicable modular design** for scale-up – enabling the accelerated full-scale commercial deployment.
- Seek to demonstrate the use of **alternative fuels** (such as biomass) and electricity for the process, enabling a calciner/ lime kiln to be zero-emissions.
- Demonstrate the ability for fast ramp up/down times for the process using electricity (switching rapidly from fuel to electricity), allowing a cement plant to undertake load balancing of renewables on the grid – enabling the **electrification** of the cement industry and a resulting low cost, local, and effective solution for grid stability with high renewable use.

2 Preliminary Front End Engineering Design – Overview

Milestone 1 (MS1) is the first milestone of the project and represents completion of the Pre-FEED phase in month 12 of the project, with the key outputs being this Feasibility Study report and a formal Go/ No-go decision by the General Assembly to confirm that the project will proceed into the next phase FEED – Front End Engineering Design phase.

The approach underpinning the Pre-FEED phase and wider project, involves the close collaboration between consortium partners and work on a number of different aspects (Research and

Development, Engineering, business case development and social engagement) to develop a successful outcome.

A series of critical tasks were required to be undertaken – pulling in the expertise from a wide range of the project's partners - to address the known risks as quickly as possible through the dedicated research and development actions, and these results used to direct and facilitate the LEILAC Demonstration Plant's design and operation. The act of addressing the known risks has been done with two objectives; ensuring that the LEILAC Demonstration Plant is successful and meets its operational goals and ensuring that the technology addresses the major issues that will be faced when applied at full scale.

The required research and development had to occur in parallel and in conjunction with the engineering activity required for the Demonstration plant. This approach has been very successful, as it was also on the LEILAC1 project – and spurred an extremely productive and intense set of work activities across all the partners. This has been assisted by drawing in expertise from across industries, countries, and professional skills.

2.1 Milestone 1 Feasibility Study – Go/ No go decision Criteria

The main purpose of the Preliminary Front End Engineering Design (pre-FEED) phase and Milestone 1 – Feasibility Study Go/ No-go decision, is to determine whether the project will proceed into the next design phase based on a number of assessment criteria. These criteria have been developed and agreed by the Executive Board, with the aim of ensuring that the developed BoD meets the project objectives and maintains the project on track for successful completion.

Feasibility Go/ No-go Criteria:

a) that the Demonstration plant's design is **technically viable**;

b) that it would **fulfil the operational objectives** of the overall project;

c) that the plant's design poses **low integration risks** for the main host plant;

d) that its cost is **within the cost constraints (+/-30%) including CAPEX and OPEX** of the budget

Key Performance Indicators (KPIs) have been developed based on these 4 criteria, which will allow the project to proceed on a risked basis, with clear understanding of the risk areas, and further development/ mitigation plans for the next phase: FEED.

Refer to **Error! Reference source not found.** for full details of the KPI's and BoD review.

3 Pre-FEED Summary – Conclusions (project rationale and approach)

3.1 A De-risking Approach

A large focus of the Pre-FEED phase has been to create an engineering Basis of Design (BoD), which establishes the design criteria and assumptions for the main systems involved in the Demonstration Plant and its integration to the host plant. Through detailed assessment of the available technical options, and a programme focussed on de-risking the development, the design has been shaped through engineering design work and the initial results of the investigations and experimental research and development activities.

Cross partner, collaborative working groups have enabled an effective de-risking process to take place, whereby unknowns technical scale up risks were identified at the beginning of the programme. The Pre-FEED phase was subsequently structured around each key component and the risks identified, with working groups focussed on design work and de-risking and validation programmes. These included engineering design works, lab scale testing, test rig construction, site visits, and the engagement of specialists for expert input.

At the outset of this work programme, a number of principles were defined which were intended to build on the successful aspects of the LEILAC 1 project. The three key factors which were identified as necessary to make LEILAC 2's de-risking programme a success, and were noted from the outset:

- A close interlink between Research and Development (R&D) and de-risking activities, and the pre-FEED and engineering design development to be undertaken.
- Maximise up-front development to the greatest possible extent. The intent is to avoid having to solve problems during the engineering phase, which results in a risk of changes and re-work.
- Focus on people rather than "full time equivalents". The makeup of the core team is critical, so a strong interlink of cross partner technical teams would need to be implemented. The team members would need to be engaged and maintained within the project to reduce flux within the team that would lead to a knowledge transfer overhead.

Through this process, the final design has been developed and de-risked. This has been built into a systems view with initial safety analysis and modelling works to identify and understand any further issues or risks. This process allows the project to move forward on a risked basis, with a detailed understanding of the remaining technical risk and capital cost (+/-30%).

3.2 The Demonstration Plant – Basis of Design Overview

The design is depicted in Figure 3 - Basis of Design (Tower Layout), showing each of the core components of the Demonstration Plant system. This design has been developed through an extensive options analysis programme during Pre-FEED, with technical options reviewed, risked assessed and design developed through R&D and conceptual engineering.

The Demonstration plant includes:

- A module of 4 LEILAC reactor tubes.
- Each reactor is designed for 10 tph input of raw meal.
- Individual cyclone pre-heat stacks per reactor tube.

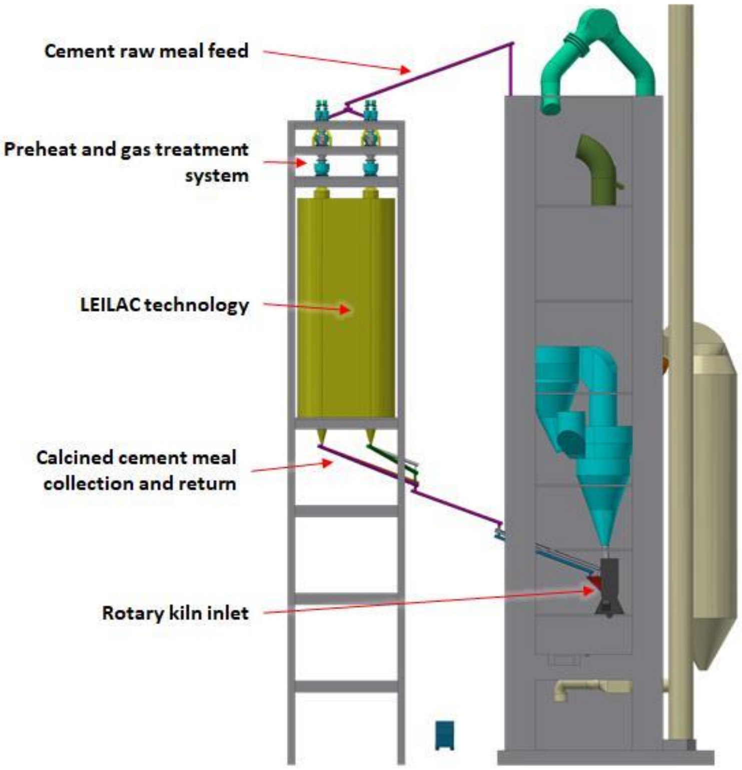

Figure 3 - Basis of Design (Tower Layout)

4 Project Design Principles & Key Design Criteria

The overarching objectives of the Demonstration plant design under the grant agreement, are to design a 4 x scale up of the LEILAC pilot plant, enabling separation of 100,000tpa of CO_2. The engineering team broke this goal down into design criteria that would be required to meet this key objective and ratified through the appropriate governance structure.

5 Options Analysis & De-risking Programme

The Pre-FEED phase of the project was focused on de-risking the scale-up of the technology and integration with the host plant. Technical, integration and other key risks were identified at the beginning of the project and mitigation plans and development programmes established, with the aim of reducing the majority of risks to low by the end of Pre-FEED / Milestone 1. Where risks could not be completely mitigated by Milestone 1, programmes would be continued into FEED for resolution and design development prior to Milestone 2 – Financial Investment Decision (FID).

At the commencement of the LEILAC2 project, the team broke down the Demonstration Plant system into components and listed the challenges with each, as well as the solutions to those challenges. This allowed a plan to be developed, including the most appropriate specialist(s) for addressing each challenge. Figure 4 - System Components & Risk Identification Process below outlines this risk identification process.

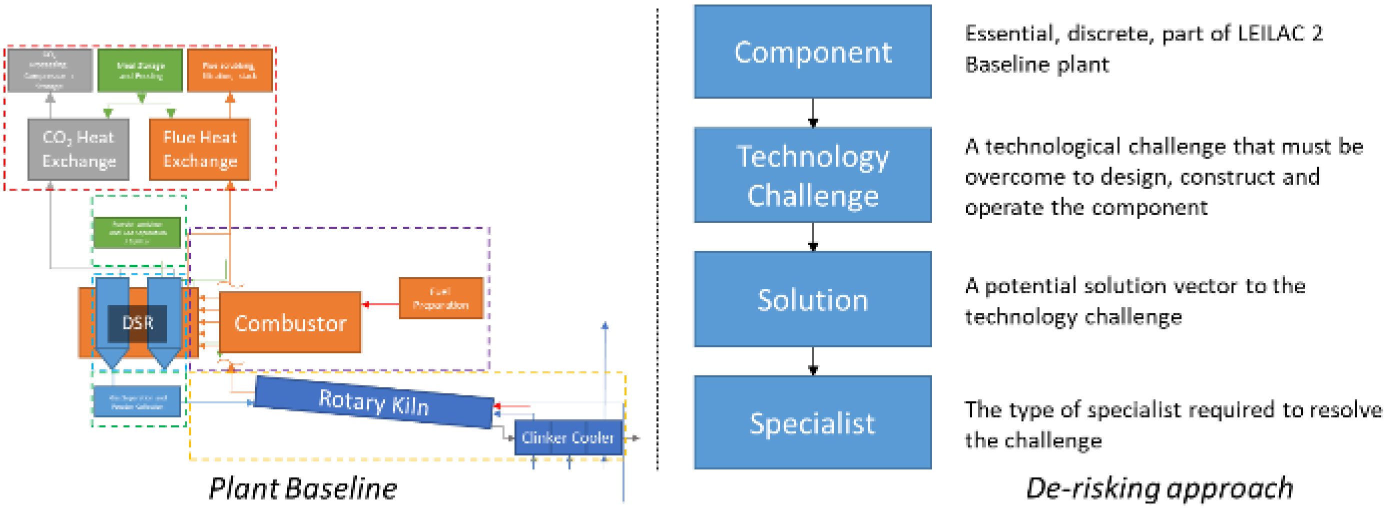

Figure 4 - System Components & Risk Identification Process

5.1 Basis of Design Risk Profiling

A key purpose of the work during Pre-FEED was to de-risk the scale up of the technology and the technology options which may be used in the Demonstration plant. Proposed solutions were assessed to determine whether they were suitable and ready (the level of risk at the time of assessment) for inclusion in the design.

A risk rating tool was developed, agreed and utilised throughout Pre-FEED phase to support technical options analysis and risk definition. The risk rating levels were defined by:

- Probability (risk rating table rows) of a risk occurring - defined with respect to the technical solution achieving its goals.
- Consequence (risk rating table columns) of the risk occurring - defined in terms of the impact of the **successful** solution, which may impact on the projects outcomes. These terms (as identified by the project Executive Board) include:

    1. The solution is technically viable;
    2. The solution fulfils the operational objectives;
    3. The solution does not result in integration risks to the parent plant; &
    4. The solution is within the cost constraints (±30% of CAPEX budget).

- The resulting consequential Risk Rating is the level of risk assigned to the item being analysed and dictates whether a solution may proceed through subsequent stage gates.

The pre-FEED phase was focussed on analysing each of these technical options with the aim of de-risking the most suitable technical options, based on the project criteria, objectives and KPI's. There were a range of technical options for each component, in cases interlinked with options from other component areas (such as type of fuel and combustion system).

At the end of the pre-FEED phase, the BoD technical options and risk profile looks remarkably different, with the options refined and the majority risk profiles reduced to low or medium.

The Milestone 1 Feasibility Study – Go/ No go decision criteria (technically viable, fulfil the operational objectives, low integration risks and within cost constraints), and the more detailed Key Performance Indicators, have been used to assess each option and ensure that the BoD (both in terms of components and full system) is fully understood, risked and wider implications on the development are known.

6 The LEILAC 2 Site – The Hannover Plant

6.1 Location

The host site is the Hannover cement production plant owned by HeidelbergCement located at: Lohweg 34, 30559 Hannover, Germany.

The Heidelberg Cement Plant in Hannover, formerly known as "Teutonia Zement", is located in the southern central part of Lower Saxony and utilizes the most northern Cretaceous limestone deposits in Germany, as does the neighbouring Höver Plant of Lafarge Holcim (right across the highway).

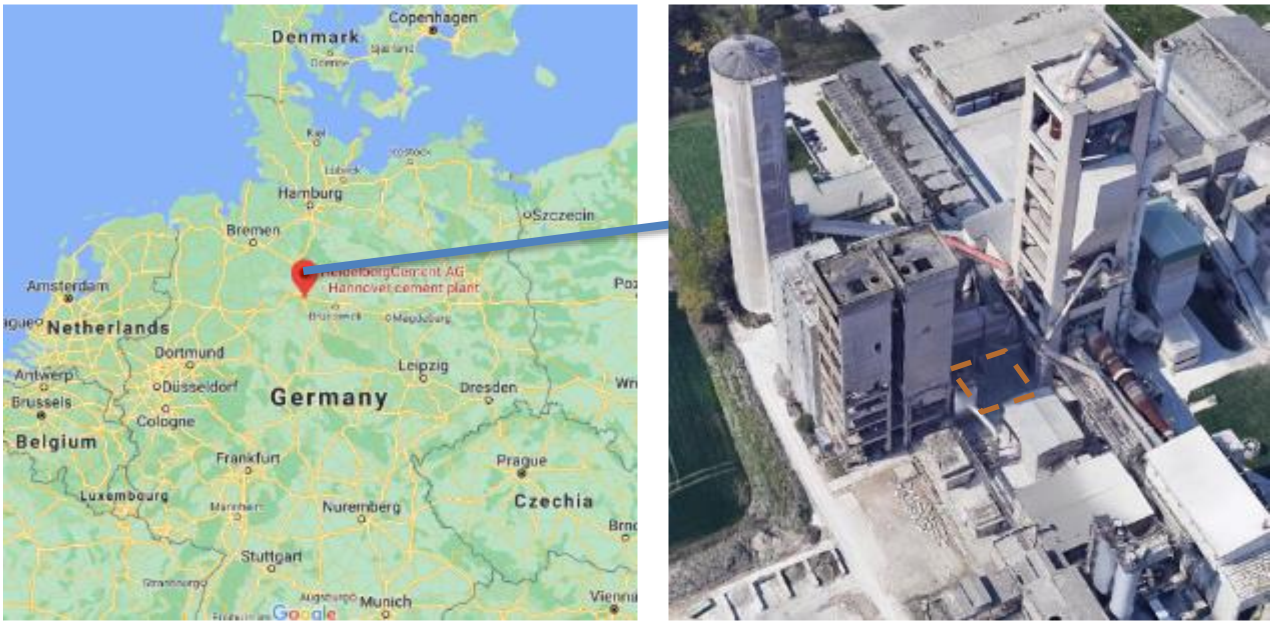

Figure 5 - Host Plant Location

The plant is located in Misburg Süd, a sub-district of Misburg-Anderten, the 5th district of Hannover. It is located between two rail lines (Figure 6), the passenger and freight transport lines in the south and the so called Güterumgehungsbahn (industrial rail transport tracks) in the north.

Right across the northern rails the so called Stichkanal (engl. branch canal) establishes a connection to the Mittellandkanal, Germany's longest artificial waterway, providing direct access to the west-east European water way transport grid for the Hannover cement plant. The plant itself is connected to its harbour by a bulk material transport bridge, conveying marl and coal as well as by a tunnel below the rail tracks and some streets.

East of the plant the Autobahn A7 provides direct connection to roadway transport, while in the south the Südschnellweg (city speed way) provides a connection to the city of Hannover.

Figure 6 - Map of western Misburg-Anderten [Open Street Map, 2021]

6.2 Site Survey

IKN commissioned a 3D laser scan of the existing Hannover plant in late 2020. From this a 3D model has been created, assisting the team with site reviews and logistics, and allowing the design team to obtain crucial dimensions and details of the site and existing plant and equipment. This model has provided critical information required to plan the integration points with the host plant in more detail.

Figure 7 - Aerial view onto Hannover plant site [Google Maps, 2021]

7 Pre-FEED Design Development – Options Analysis & Risk Reduction

A key focus of the Pre-FEED phase, was to minimise the known risks associated with developing, implementing and the scaling up of the LEILAC technology. Following the identification of all potential technical challenges and possible solutions, the working groups proceeded with the design development of each individual component area based on an options analysis approach. The LEILAC2 KPI's and overall system requirements for the Demonstration Plant were used to assess each design option to ensure that the design met not only the technical requirements of the component itself, but also supported the success of the wider system design criteria, and the process and integration philosophy.

The sections below provide a summary of the outcomes of the options analysis work.

7.1.1 Tower Location

The optimal position of the LEILAC2 tower on the Hannover host site, has been investigated and a number of potential locations identified. Each location has been fully assessed to ensure the distance from the existing preheater tower was minimised (to minimise the horizontal distances for raw meal feeding and the hot meal transport from LEILAC2 back to the host plant kiln), but also to ensure that the tower location (both during construction and operations) did not disrupt the host plant operations or maintenance activities, and that there were no major safety or constructability issues.

7.1.2 Integration & Heat Exchange

Integration Philosophy

The Demonstration plant will be subjected to the operating conditions of its host plant, given its close integration - allowing both the performance and integration of the technology to be validated. The maintenance, modifications, and enhancements (improving efficiencies, aiding risk mitigation, and scale up steps and commercialisation) will be an important step, with a key aim being operations and integration efficiency.

Feed Return Point(s)

The final feed return point will see the LEILAC system's calcined meal being conveyed directly into the host plant kiln inlet. This return point will require the meal to be returned at a high temperature and high calcination.

Meal Preheat

Two key options were considered for the preheat stack(s):

1. Individual preheat stacks (1 per reactor tube)
2. Combined preheat stack providing preheated meal to all 4 reactor tubes

Individual preheat cyclone stacks have been included in the Basis of Design for the LEILAC2 Demonstration plant.

7.1.3 LEILAC system

The LEILAC reactor Design

The Demonstration plant Basis of Design includes a module of 4 LEILAC reactor tubes. Each reactor is designed for 10 tph throughput of raw meal.

The LEILAC reactor development has progressed significantly as a result of LEILAC 1's test programme, which has provided data necessary to improve the modelling of the reactor.

Reactor Materials Selection

LEILAC 2 reactor tubes will be in contact with both cement meal in a CO_2 environment and combustion products resulting from the combustion of solid fuels (in the combustor). The combustion products in particular can contain highly corrosive products, containing elements such as chlorine and sulfur, present in both the ash and in the gaseous phase.

LEILAC1 pilot has run successfully with a type of alloy able to withstand high temperatures. The LEILAC2 Basis of Design will include this material. However, further testing on this and alternative alloys will be undertaken and the design reviewed at the end of the FEED phase.

7.1.4 Furnace & Combustion System

The LEILAC 2 consortium engaged a specialist company – FCT Combustion[3], who were tasked with the concept design of a combustion system that could achieve maximum RDF (Refuse Derived Fuel) use allied to acceptable thermal efficiency in the reactor.

Given the specific requests of the process and previous experience of the Calix team with the LEILAC1 pilot plant, the concept design of the combustion system and furnace went through substantial optimisation along the study. FCT Combustion used Ansys Fluent CFD (Computational Fluid Dynamics) code for the modelling of the reactor furnace and in-house models for the calculation of combustion parameters.

After running CFD models of several module furnace geometries, boundary conditions and combustion calculations, the design team arrived at a potential solution.

Electrification - Retrofit Ready

Another aspect of the LEILAC2 programme is testing the electrification of the LEILAC reactor. Retrofitting electrical elements to an existing plant is difficult and potentially expensive. Therefore, the LEILAC reactors are being designed as 'electric-hybrid retrofit ready', to enable electrification easily and without significant redevelopment cost.

The Basis of Design for the LEILAC 2 demonstrator includes the proposed additions necessary to make it "retrofit ready".

7.2 Modelling & Technical Validation

7.2.1 Process development, modelling and validation

Process Modelling provides detail on:

- The effect of design on the LEILAC 2 Demonstration Plant's operation and costs.
- The effect of the LEILAC2 Demonstration Plant's operation on Hannover's existing operations.

Politecnico di Milano (Polimi) have performed detailed process modelling during the Pre-FEED phase, with support from HTC, Calix, Hannover and IKN.

The process model of the host cement plant in Hannover and of the LEILAC2 Demonstration plant have been developed using the commercial software system Aspen plus, in order to compute the mass and energy balances.

The modelled temperatures along the preheater are in very good agreement with the measured data from the host plant, with a maximum difference of about 10°C and the total fuel consumption is also well aligned with the data from the engineering simulation.

[3] https://fctcombustion.com/

The model of the LEILAC2 Demonstration plant has been integrated into the Hannover host plant model.

7.2.2 CFD Modelling

During this working period, CERTH undertook CFD modelling, mainly focused on the furnace design optimization, according to the operational configurations proposed at the start of the project. In the framework of this analysis, the following design aspects have been examined:

- Optimum reactor arrangement
- Optimum flue gas inlets/outlets arrangement (e.g. staging concept) and number of them;
- Optimum reactor height/diameter
- Optimum reactor in-between distance and distance from the furnace walls
- Optimum mass flow rates/temperature values of the flue gas at the injection points

For this reason, a proper steady-state 3D computational fluid dynamics (CFD) model has been developed in ANSYS Fluent platform (v18.2). This model takes into account the heat transfer inside both the furnace and the reactors along with the calcination reaction kinetics for a higher accuracy of the derived results.

The parametric study produced a number of outcomes, which were subsequently utilised for other aspects of the project. Further development will be required during the feed phase to determine final design values, however this first phase of work has been instrumental in instructing the team about important design parameters and their consequences.

7.2.3 Experimental campaigns in Calix operating calciners

Calix owns and operates several calciners which operate in manners similar to that which will be installed at LEILAC 2. Two of these have run campaigns in support of the LEILAC2 design development. These are the natural gas-fired LEILAC 1 pilot (Lixhe, Belgium) and the electric e-DS (Bacchus Marsh, Australia). Both calciners are a single tube within a furnace. LEILAC 1 has a nominal throughput of 10 tph and the E-DS, with its smaller diameter, can process a few hundreds of kilogrammes per hour.

These trials have provided an understanding of the performance of raw meal from the Hannover plant in the LEILAC technology.

7.2.4 Environmental – Impurities modelling

Environmental management is a priority for the LEILAC 2 demonstrator design in order to ensure safe operating conditions and also operations within the allowances for the existing Hannover plant. Emission levels from the LEILAC Demonstration Plant are not expected to be any higher than the host plant process, particularly with the aim of using the host plant fuel mix. However, in order to demonstrate and validate, a number of environmental measurement campaigns have been developed and will be undertaken during FEED phase, to measure the impurities when processing the meal produced from the quarries in Hannover.

8 Health, Safety & Environment

8.1 HSE Design Philosophy

A focus on health, safety and environmental issues is inbuilt within the project objectives and design philosophies for the development of the Demonstration plant.

- Health and safety shall meet all required standards and policies from the commencement of the project through the entirety of the plants lifetime to the decommissioning of the plant.
- Environmental issues shall be proactively managed and shall meet all approval conditions and standards.

The LEILAC consortium and design team is committed to incorporating safety into all levels of the design process, with ongoing hazard analyses and risk assessments throughout the design process. A key responsibility of the engineering team is to identify, evaluate and control hazards.

As part of phase 2 – the FEED study, a formal, detailed HAZID (Hazard Identification Study) / HAZOP (Hazard and Operability Study) analysis review will be undertaken.

Purpose of HAZID / ENVID:

The purpose of a Hazard Identification Study (HAZID) is to carry out a qualitative hazard identification and assessment of the project facilities. The main objective is to undertake the HAZID early in project life to identify key issues for resolution. This is done by the systematic identification of any hazards, which may have the potential to cause harm, followed by a review of whether adequate safeguards exist, or whether additional safeguards are required to mitigate the potential consequences.

An ENVID (ENVironmental aspects IDentification) Review is a systematic assessment of a plant, system or operation intended primarily to identify environmental aspects and potential impacts. The method is often used during projects as a basis for risk assessment. The purpose of an ENVID Review is to:

- Identify the environmental aspects/potential impacts and opportunities generated by the project or activity under review in a structured fashion
- Identify appropriate mitigation techniques to ensure the potential impacts are effectively managed
- Provide input to the qualitative Aspects Register and develop a risk ranking of the impacts to ensure that the significant elements are suitably addressed in a timely manner
- Provide input to an action tracking process to ensure that all the environmental aspects and potential impacts identified are addressed in a suitable manner.

The review attempts to identify the environmental aspects and potential impacts generated not only by the activity but also those caused by interactions with the surrounding environment. It is a holistic study which attempts to capture all the issues of the project. The review should also be used as an opportunity to explore and capture sustainability aspects of the project if appropriate.

9 Project Delivery

9.1 Procurement Strategy

The host cement plant in Hannover is well connected to the motor-, rail- and waterway system in northern Germany. Therefore, even large pre-assembled packages of equipment can be easily transported to the site, with a number of transport options.

9.2 Construction Planning

The wider site has been investigated to understand key / available construction areas and ways to minimise disruption to the host plant. This plan is conceptual only and has not been fully ratified or agreed (particularly potential areas for prefabrication of materials and storage). The construction plan will be further developed and detailed during the FEED stage.

To minimise disruption to the host plant during construction and installation, the constructability review included outline planning and review of key construction stages. All plans are subject to the appropriate permits being in place.

10 Value Assurance Review

As an initiative by Calix and the LEILAC2 Executive Board, an independent Value Assurance Review (VAR) was undertaken at the end of the pre-FEED phase, with the objective to support the General Assembly (Consortium) decision to proceed to phase 2 - FEED. This review would:

1. Assess whether the LEILAC2 project team is ready for the FEED phase i.e. conclude a robust Basis of Design and progress to Front End Engineering and Design (FEED) to meet Final Investment Decision criteria.
2. The review would also determine whether the plan and cost estimate to progress the overall development to the next decision point are sound and adequately resourced.
3. Provide assurance to the General Assembly that major technical/ business uncertainties/ issues that constitute major risk have been identified and that adequate plans to address these risks are in place.

VAR Team:

Although the VAR Team consisted of consortium partner representatives, the individuals were independent to the LEILAC2 project.

Calix (Review Leader)	Non-executive Director of Calix Limited
HeidelbergCement	Technical Director
Cimpor	Director of Co-processing & Renewable Energies Area
CEMEX	Cement Quality and Environmental expert

Key Findings:

- Project team and process comes across as very well run.
- The work through pre-FEED is very detailed, thorough and well structured.
- The de-risking approach adopted was well thought through, and the risks as at pre-FEED are a fair overall representation of the project's current status.
- Learnings from LEILAC 1 appear to have been studied, and resulting knowledge adopted in the approach for LEILAC 2.
- LEILAC 1 is an excellent asset for contributing to de-risking LEILAC 2 components through FEED, and beyond.
- The LEILAC projects' profile is already high given current levels of external stakeholder interest.
- A list of actions for the FEED phase, that will be tracked by the Executive Board, were provided – noted that these are all included within the plans for FEED.

The VAR team supported that the LEILAC 2 project is ready to enter FEED.

11 Preliminary Front End Engineering Design

11.1 Basis of Design

Through the technical options analysis and de-risking process, the design has been developed in line with the Project Objectives, Milestone 1 Feasibility Study – Go/ No go decision Criteria and "Figure 8 - Process Configuration".

In summary, the BoD includes:

- A **module of 4 LEILAC reactor tubes**.
- Each reactor is designed for **10 tph throughput**.
- **Individual cyclone pre-heat stacks** per reactor tube.

11.2 Basis of Design – Process Configuration

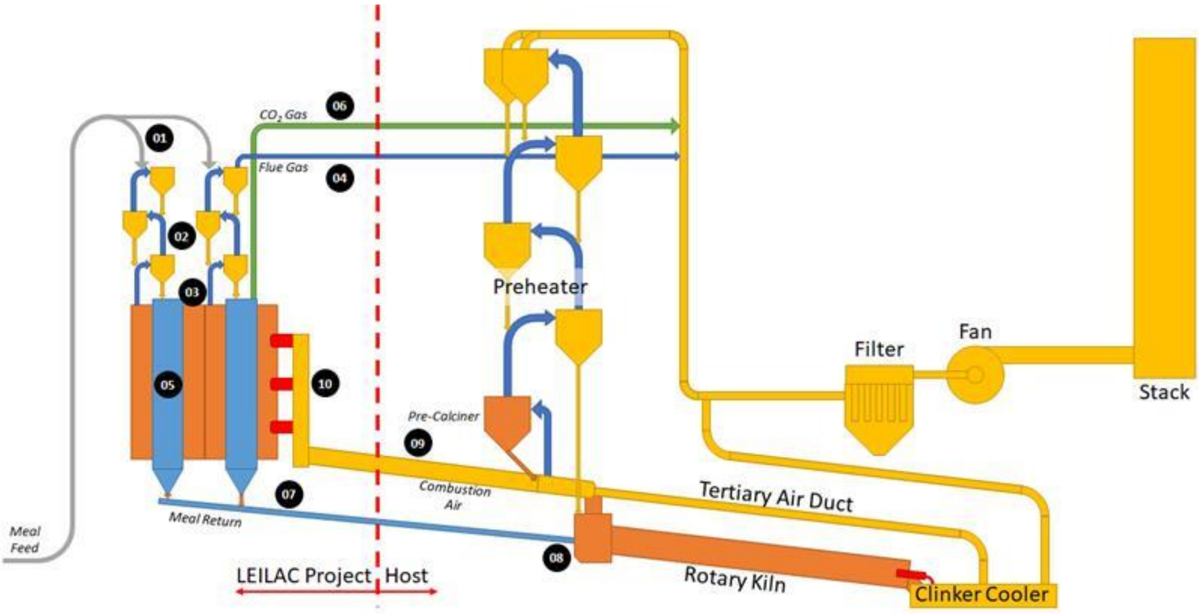

Figure 8 - Process Configuration

Description of the LEILAC2 Demonstration Plant process, as depicted in Figure 8 - Process Configuration**:**

1/ Raw cement meal transferred from the host plant and fed equally into the LEILAC reactors.

2/ The raw meal is heated by the flue gas discharged from the LEILAC furnaces. This occurs within parallel trains of preheat cyclones.

3/ The preheated material is transferred from the preheat system into the LEILAC reactors.

4/ Flue gas from the preheat cyclone stacks is discharged into the host plant's gas treatment system and finally is discharged via the stack.

5/ The meal is calcined within the LEILAC reactors, with the CO_2 discharged at the top and calcined cement meal discharged at the base.

6/ The CO_2 is cooled, and its quality measured before it is discharged to the host plant's gas treatment system.

7/ The calcined cement meal is collected from the LEILAC reactors for return to the host plant.

8/ Transfer of material directly into the kiln inlet chamber.

9/ The LEILAC furnaces use preheated combustion air from the host plant's clinker cooler.

10/ The burners may run on a variety of solid and gaseous fuels including Refuse Derived Fuel (RDF), coal, natural gas, hydrogen (and potentially electricity).

12/ Samples of gas and solids can be extracted from a number of locations to measure plant performance.

12 Pre-FEED Cost Estimate

12.1 LEILAC2 Demonstration Plant Budget

The budget for the Demonstration plant design and construction is split across grant funding under the European Commission H2020 grant agreement, cash contributions from industrial partners and in-kind contributions for staff by all partners.

Total Project Budget split:

€16m (requested grant for the demonstration plant and R&D, by the European Commission)

€18m (in-kind contribution)

Total €34m of budget allocation

Demonstration plant build itself is expected to be around €16m.

12.2 Pre-FEED CAPEX Cost Plan

An important element of the Pre-FEED phase is the development of the Cost Plan, which at the feasibility stage has accuracy of +/- 30%. To ensure this level of accuracy is achieved, the cost plan has been developed through:

1. Scale up of LEILAC 1 build costs by Calix.
2. Bottom-up budget development based on LEILAC2 BoD, detailing out the equipment and materials required and costing the procurement and construction approach. This was undertaken by IKN.
3. An independent budget estimate by a member of the LEILAC1 construction management team.

12.3 OPEX Costs

A detailed process and technoeconomic model has been developed, to provide OPEX analysis to feed into the options analysis work. This model has been validated against the process model.

This modelling provides details of the additional OPEX requirements over and above the Hannover host plant, both in terms of EUR/ t.ck-e (euros per ton of clinker equivalent) and EUR/t.CO2. This information has been modelled for a range of scenarios, and the results of the BoD scenario, and some alternative heating options.

OPEX **Key Conclusions:**

- Detailed OPEX modelling has been undertaken, should the design work as planned, it is anticipated that the LEILAC2 would separate at a cost in the order of **€10/t CO_2 extra OPEX** (excludes compression costs and CAPEX depreciation costs, etc., which are expected to be in the region of an additional €10-€15/t CO_2). **Therefore, total costs of the first-of-a-kind LEILAC carbon capture plant is in the region of €25 /t CO_2.**
- The development demonstrates and maintains the vision for no significant additional OPEX for the LEILAC technology, with a very competitive CAPEX.

13 Pre-FEED Results and Next Steps

13.1 Conclusions

The LEILAC2 governing bodies have reviewed the Feasibility Study undertaken during Pre-FEED, and can confirm that all project objectives and technical and economic criteria have been met and key risks have been identified, with appropriate de-risking strategies implemented or to be continued during the next phase – FEED.

It is therefore the Consortiums formal decision that the Project is to proceed into FEED, with Milestone 1 Go / No-go decision confirmed as a "Go".

The project will now proceed into the FEED phase (commencing April 2021), resulting with Milestone 2– Financial Investment Decision, at which there will be a further Go/ No-go decision based on a +/- 15% cost plan.

13.2 Milestone 2 - FID

Milestone 2 – the Financial Investment Decision (FID), falls at the end of the FEED phase. The FID will be made by the General Assembly (project consortium), following detailed review of the FEED study to ensure that the project design will achieve the project objectives, as specified within the grant funding agreement.

The FID is the point at which in kind cash contributions will be formally committed by consortium partners. This investment by partners will be made based on the FEED study and the +/- 15% cost plan.

14 Abbreviations

BoD	-	Basis of Design
CFD	-	Computational Fluid Dynamics
CO_2	-	Carbon dioxide
EC	-	European Commission
ENVID	-	ENVironmental Impact IDentification
DSR	-	Direct Separation Reactor
FAD	-	Free Air Delivery
FEA	-	Finite Element Analysis
FEED	-	Front End Engineering Design
FSI	-	Fluid Solid Interaction
gPROMS	-	PSE's advanced process modelling product
H&MB	-	Heat and Mass Balance
HAZID	-	HAZard IDentification
HAZOP	-	HAZard and OPerability Study
HSE	-	Health, Safety and Environment
KPI	-	Key Performance Indicators
LEILAC	-	Low Emissions Intensity Lime and Cement Project
LHV	-	Lower Heating Value
LPM	-	Litres per Minute
RAS	-	Reverse Axial Separator
R&D	-	Research and Development
PRE-FEED	-	Preliminary Front End Engineering Design
P&ID	-	Piping and Instrumentation Diagram
PFD	-	Process Flow Diagram

SI	-	International System of Units
TBD	-	To Be Determined
tpa	-	tonne per annum
tph	-	tonne per hour